Maui Space Surveillance System (MSSS) Satellite Categorization Laboratory

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Abstract

The Maui Space Surveillance System (MSSS) satellite categorization laboratory is a fusion of robotics and digital image processing that aims to decompose satellite photometric characteristics and behavior in a controlled setting. By combining a robot, light source and camera to acquire non-resolved images of a model satellite, detailed photometric analyses can be performed to extract relevant information about shape features, elemental makeup, and ultimately attitude and function. Using the laboratory setting, a detailed analysis can be done on any type of material or design and the results cataloged in a database that will facilitate object identification by "curve-fitting" individual elements in the basis set to observational data that might otherwise be unidentifiable.

The newly created laboratory utilizes an ST-Robotics five degree of freedom (DOF) robotic arm, collimated light source and non-focused Apogee camera have been integrated into a MATLAB based software package that facilitates automatic data acquisition and analysis. Efforts to date have been aimed at construction of the lab as well as validation and verification of simple geometric objects. Simple tests on spheres, cubes and simple satellites show promising results that could lead to a much better understanding of non-resolvable space object characteristics.

This paper presents a description of the laboratory configuration and validation test results with emphasis on the non-resolved photometric characteristics for a variety of object shapes, spin dynamics and orientations. The paper concludes with a discussion of the utility and benefits of the laboratory to the space situation awareness (SSA) community as a whole are discussed, as well as plans for the future.

1. Introduction

Since the beginning of the Air Force Space Command's (AFSPC) counterspace mission, space situational awareness (SSA) has played a pivotal role in the space object identification (SOI) portion of that mission. This task is uncomplicated for objects of relatively large size that can be accurately resolved. As military and commercial satellites and other space objects decrease in size to the nano and micro regime, SOI becomes increasingly difficult. Radar allows one way to keep track of objects, but a large amount of a priori data about the object is required to make a positive identification as well as to determine the object's current functionality or mission. Optical sensors provide additional SOI capabilities and for objects that can be resolved, this technique can provide additional data with respect to radar tracking. However, optics based object characterization has traditionally been used for resolvable objects. When objects are too far away, too small, or at poor angles to the sensor, the amount of spatial information diminishes rapidly. In most cases the count of photons that are captured by the charged coupled device (CCD) camera is the only data available.

Many techniques are currently available for non-resolvable object characterization, the most common being forward modeling and data inversion. While both methods have benefits, they have limitations that can significantly reduce confidence in SOI predictions and object characterization. Bridging the gap between purely theoretical analysis and operational analysis might eliminate some of these limitations, and supplement the counterspace and space superiority mission of the US.

The solution outlined below is a laboratory that allows in-depth analyses of basic shapes and complicated models of orbiting satellites in virtually any configuration with the observing site, sun and satellite. By analyzing the objects in a controlled environment, atmospheric distortions and other line of sight anomalies that are encountered with observational astronomy are eliminated using a more "physical" model of object-light interactions than one would have with computer simulations.

2. Laboratory Construction

Construction of the lab began in 2004 at the Remote Maui Experiment (RME) site in Kihei, HI. Present capability includes an ST-Robotics R17 5-axis articulated arm robot, Apogee 9E CCD camera, Oriel 13W white light source, 4'x8' drilled optics bench, custom made collimator, and a Dell workstation running Windows XP, Software Bisque's The Sky and MATLAB 7. Each piece of equipment was mounted on an optics bench in a manner that provided maximum dynamic range of movement so as to allow effective 3-degree-of-freedom system simulations (Fig. 1).

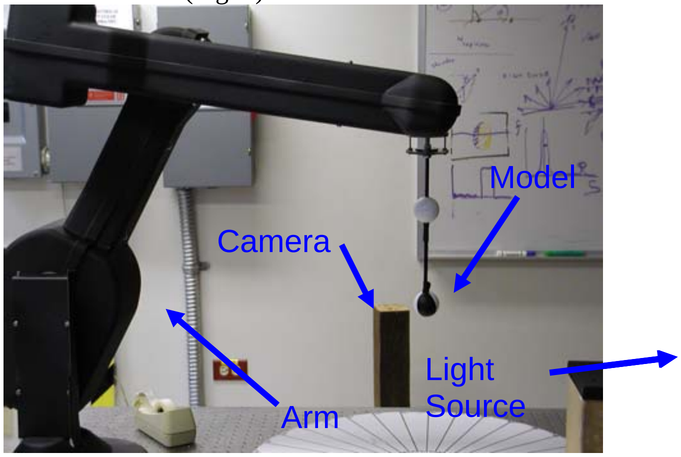


Fig. 1. Laboratory Setup

The camera and light source were positioned on independently adjustable rails so as to achieve control over phase angles and distances used to estimate relative intensity. In order to ensure that the robotic arm was out of the field of view (FOV) a 23 cm extension was added to the "hand" of the robot in order to mount the models. The arm and the arm extension were painted with ultra-flat black paint in order to reduce reflecting surfaces.

Since the original light source did not produce a sufficiently collimated beam, the research team constructed a collimator using a piece of sheet metal and cardboard baffles. The inexpensive, homebuilt collimator performed well, providing a reasonably coherent light source with a diameter of about 2.5” (Fig 2). The relatively small collimated beam was required for use of small satellite models.

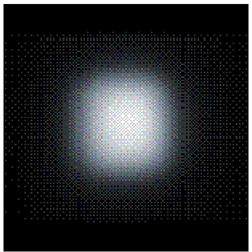
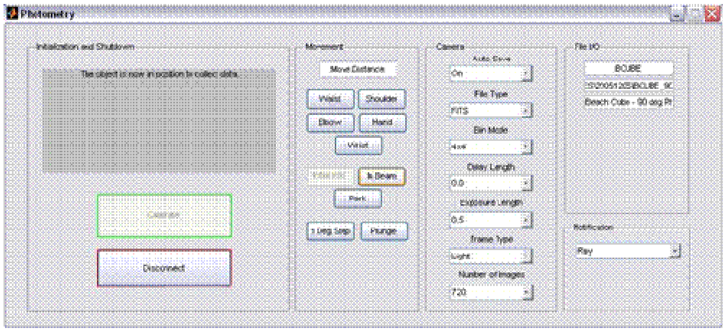


Fig. 2. Example Collimated Beam

One of the most significant requirements of this project was to enable a user of the system to input the general set of experiment constraints, and return the process control when the data had been taken and the analysis was complete. Photometric analysis tools were written in MATLAB, while the camera was controlled through a custom Visual Basic interface, and the robotic arm was controlled by a 4th generation language called Forth. The research team created a graphical user interface (GUI) in MATLAB (Fig. 3) that allowed the user to monitor the startup and initialization of the robotic arm, place the object in its home position, command the arm to move the object in a manner that reflected the user’s desired orientation to the light source and observing sensor, capture, download, process and compress images of the object at user defined intervals, create an output graph of intensity versus time or position and a video of the processed images, raw images, and produce a photometric intensity graph (Fig. 4). The process control software was written in MATLAB in order to speed development and provide proof-of-concept for the initial verification and validation of the lab and the processes within it.



The object is now in position to collect data.

Auto Save: On
File Type: FITS
Bin Mode: 4x4
Delay Length: 0.0
Exposure Length: 0.5
Frame Type: Light
Number of Images: 720
BCUBE
Beach Cube - 90 deg Pl
Play

Fig. 3. MATLAB GUI

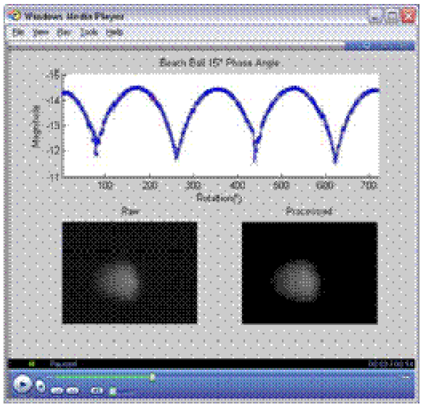


Fig. 4. Sample Output Video

In order to effectively model movement of satellite, a number of constraints had to be considered: 1) the light source and camera had to be adjusted by hand and could only be used in one plane parallel to the top of the optics bench, 2) the size of the collimated beam was very small and limited our lateral movements as well as the size of our models, and 3) the arm extension required that target models be placed 23 cm from the normal reference of the robotic arm. The small collimated beam produced a requirement that the test object be rotated to model orbital or rotational effects without deviating more than about 4 mm from the home position of the object. The GUI application provides the capability for rotation about any of the three axes or combination thereof. This rotation is achieved by transforming the coordinate frame of the robot into the frame of the object, then displacing the origin with respect to the object center, thereby providing an arc through space that the test object will follow. The test object will also be turned as per instructions (Fig. 6). Combining three degrees of freedom with the ability to mount the model in nearly any configuration allowed orbital dynamics to be mimicked to a limited degree. This limited degree of control was acceptable for validation and verification of the process that was developed, but would not be sufficient for higher fidelity modeling. A new package has been built that takes pointing and ephemeris data from a Java interpretation of the NORAD SPG4 algorithm and converts it into robot position movements in order to accurately model the path of a satellite over any designated site. This allows the user

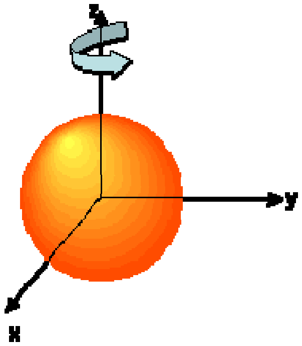


Fig. 5. Single Axis Rotation

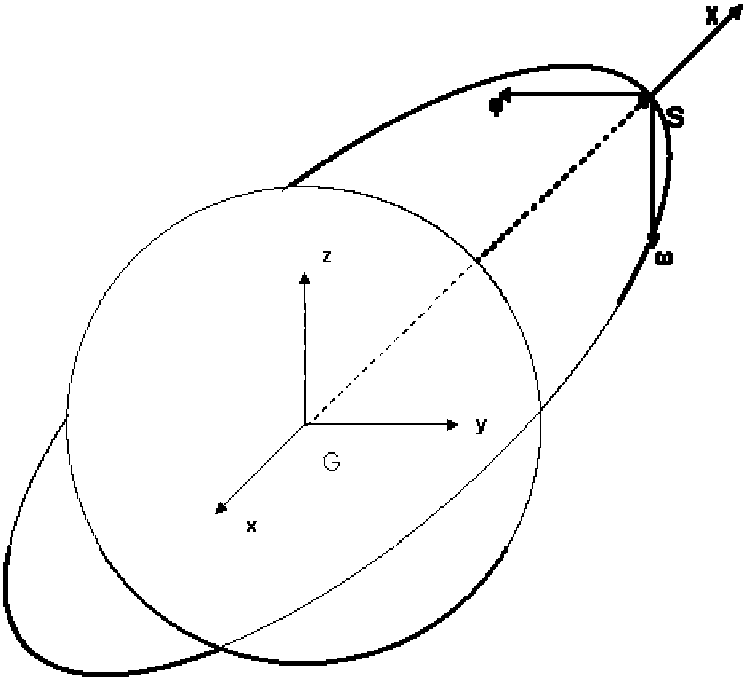


Fig. 6. Object Orientation

a significant amount of control over the data that is collected and will allow direct comparison to computer simulated data and observational data.

The software is designed to default into an over sampling mode in order to get the most complete data set about a test object. This over sampling can be equated to turning a sphere 1 degree then taking an image, turning another degree then taking another image and so on, over many full rotations of the object. This reduces the risk of anomalous data being captured when implementing “continuous” sampling. A number of features have been added to the software that allow varying degrees of fidelity to the analysis: a dark image can be taken at the beginning of each data run, selected binning settings can be utilized, and for validation and verification a control object can be placed on the mount in such a way that the control images are interleaved with the test images to allow for background reduction and albedo reference measurements.

The current reduction step is relatively uncomplicated. It first reduces the raw image (Fig. 7) by subtracting the dark image (including bias) from the image in question, determines the area of the object in question and performs a linear stretch of the area of the object to produce the final image (Fig. 8). It then produces a count of the cells within the matrix that holds the image data. This count is plotted with the corresponding time or position to produce a light curve for the object. This process does require throwing away some edge data by linearly stretching the image, but has produced promising results. A raw light curve can be obtained by simply summing the number of photons that are represented in each cell of the matrix; however this method allows a substantial amount of noise to invade the system.

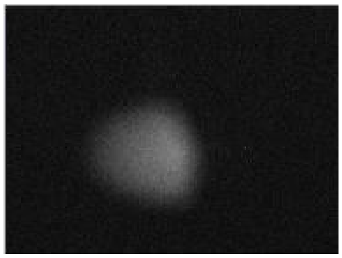


Fig. 7. Raw Image

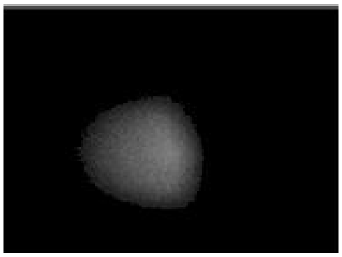


Fig. 8. Processed Image

Data collection is done in an extremely low-light environment, made possible by covering leaking areas in the joint between the collimator and light source, painting the arm and arm extension black in order to reduce reflection, taping or blacking out LED’s and other small light sources, and coding the MATLAB software to shutter the screen just before and during the acquisition of an image. These steps have successfully reduced a substantial portion of image noise.

3. Initial Results, Validation and Verification

The test parameters included an initial phase angle of approximately 15° (a physical limitation of the system), and a maximum of 90°. All validation and verification analyses were run once each at the minimum and maximum phase angles. Each run consisted of two to four full rotations of the object at one degree steps, with an image taken at each step. The images were taken in a 4x4 binning mode. Each set of images were processed, the results displayed to the user and saved to an archive directory.

The first test object was a sphere. A ping pong ball (sphere) satisfied the size and regularity requirements for mounting and observation. The sphere was rotated in the X-Y plane and the photometric curve of the sphere was nearly flat, as expected, and minor observed deviations could be explained by specular and diffuse reflectance of the object and the coat(s) of paint. The photometric differences between 15° and 90° were minimal. Minor corrections were made to the analysis code based on this test case.

A solid white cube was second test object analyzed. The results at 15° phase angle showed a periodic curve with small amplitude caused by diffuse and specular effects due to the geometry of the face. The analysis algorithms were adjusted in order to account for the increased specular reflection from the flat face. A phase angle of 90° demonstrated more irregularity in the light curve, shown by larger amplitude and large instabilities in the troughs. This is caused by diffuse effects of ambient light on the non-illuminated side.

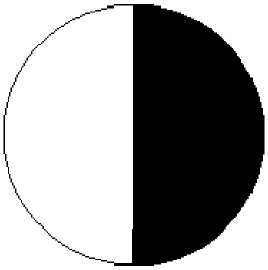


Fig. 9. Sphere Coloring

The third test object analyzed was a sphere painted white and black over alternating quadrants (Fig. 9). When observed at 15° phase angle, a very regular light curve was evident (Fig. 10). It should be noted that the noise in the troughs is due to the specular component of the paint on the black quadrant. At a 90° phase angle there is a marked decrease in the average magnitude of the signal (~13.4 - ~12.7) as well as large anomalies in the troughs of the curve. These anomalies appear to be caused by specular reflection from the black paint when all white paint is not visible.

The fourth test object analyzed was a cube with each quadrant painted alternating black and white. The resultant curve at 15° phase angle was similar to the black and white sphere except for peak and trough effects (Fig. 11). Unlike the sphere, the cube shows pointed peaks and more instability in the trough. Both effects can be described as a "glint" from the flat surface of the object. The data from the object at the maximum phase angle was prone to poor data capture and analysis (Fig. 12). Peak and trough effects were similar to the minimum case. Remounting the cube and adjusting the sensitivity of the analysis algorithm increased the quality of these measurements.

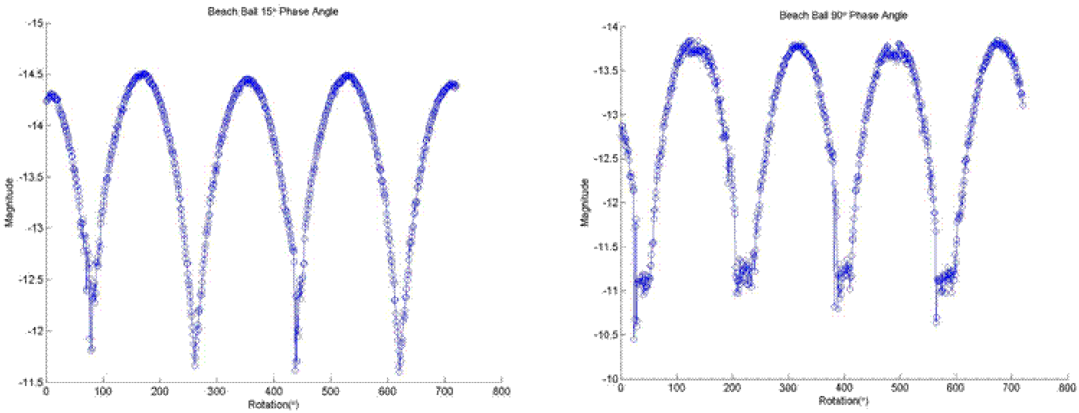


Fig. 10. Beach Ball Light Curves

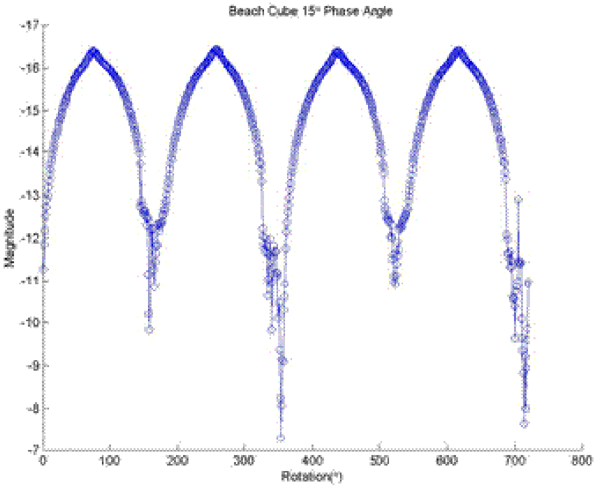


Fig. 11. Beach Cube 15° Phase Angle

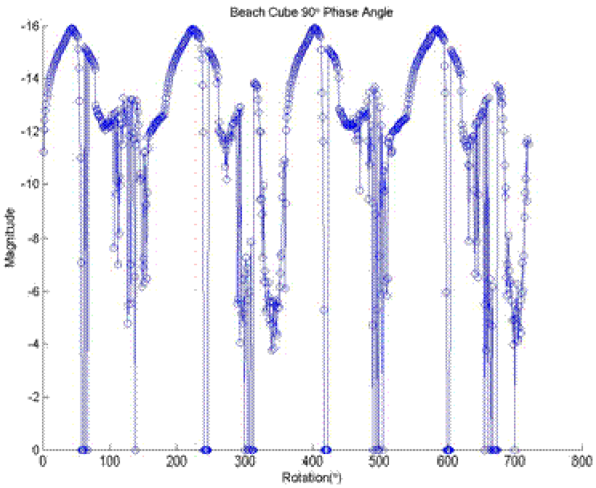


Fig. 12. Beach Cube 90° Phase Angle

The fifth test object was a replica of an Atmospheric Neutral Density Experiment (ANDE) sphere (Fig. 13). The ANDE spheres will be highly monitored and should provide excellent comparative data. The results of the data gathering at 15° phase angle showed similar behavior to the black and white sphere (Fig 14.). The curved troughs indicate that the white band about the equator of the sphere helps normalize the signature when the black quadrant is dominant in the field of view. The 90° phase angle case also differs from the corresponding data from the black and white sphere (Fig. 15).

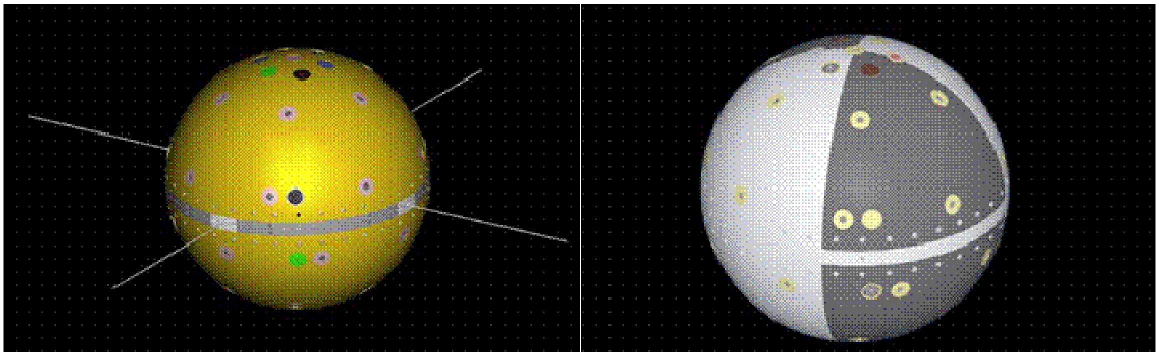


Fig. 13. ANDE Sphere Configurations

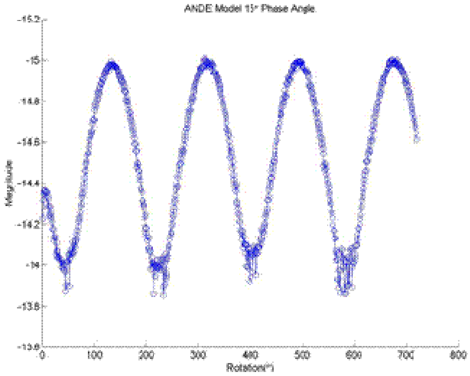


Fig. 14. ANDE Light Curve
15° Phase Angle

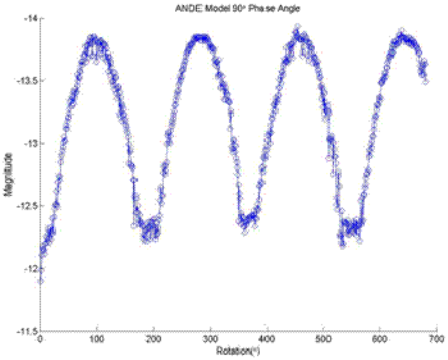


Fig. 16. ANDE Light Curve
90° Phase Angle

4. Conclusions, Thoughts and the Road Ahead

Although limited validation and verification of the techniques and hardware have been performed, the results show promise for helping bridge the gap between modeled and observed data. The ultimate goal is to build this capability into a program that will be able to take over-sampled data on complex objects following complex trajectories, comparing the data to less sampled objects, adding distortion and other physical sources of error. in order to better identify, classify, and characterize the missions and behavior of space objects. The first small step toward this goal has been achieved by integrating an initial set of hardware, creating a set of analysis algorithms and performing a limited validation and verification of the concept and methods. The next phase of validation will involve taking extensive measurements of simple shapes to determine robustness of the system, and also comparing results from the lab to actual data from known space objects such as the ANDE spheres. This capability should evolve into a tool that can be used to accurately predict the signature of unknown non-resolvable objects, as well as providing a better understanding of the space environment.

5. Acknowledgments

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2. http://exploration.nasa.gov/programs/station/STP-H2-ANDE.html, *NASA - Exploration Systems – Space Test Program-H2 – Atmospheric Neutral Density Experiment (STP-H2-ANDE)*. 2006.